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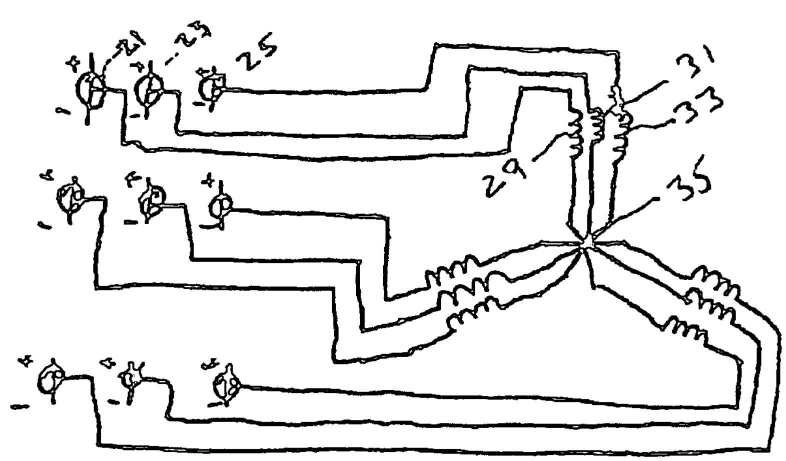
(54) Title: APPARATUS FOR PARALLELIZED OPERATION OF SEMICONDUCTOR SWITCHES



(57) Abstract: A switching circuit for an inductive load including at least one voltage source and a plurality of half bridge switching circuits, each half bridge switching circuit having a pair of serially connected switches, each switching circuit being coupled across the at least one voltage source. A plurality of inductive loads (29, 31, 33), wherein each inductive load (29, 31, 33) is coupled between the junction of each a different pair of serially connected switches and a node. The plurality of inductive loads (29, 31, 33) is inductively coupled to each other and is preferably a plurality of windings wound together to form a coil of a motor. The motor can be of any type including one having a plurality of phases, wherein a plurality of coils is associated with a different phase of a motor.

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Apparatus for Parallelized Operation of Semiconductor Switches

Technical Field

This invention relates to circuitry for providing power to a load via a plurality of parallelized semiconductor switches.

Background Art

Semiconductor switching devices, such as, but not limited to silicon controlled rectifiers (SCRs), field effect transistors (FETs), bipolar junction transistors (BJTs), insulated gate bipolar transistors (IGBTs) and the like, are well known in the art. One function of such switching devices involves control of relatively large current flow from a high voltage source with the requirement of only small power inputs to the switch to provide switch control.

One such control function of these semiconductor switches is control of electric power to inductive loads, for example, the windings of an electric motor. With increased power requirement, it is apparent that the semiconductor switch can be enlarged to provide this increased power requirement. A problem with this increase in semiconductor size is that the cost of fabrication of such devices has a maximized cost/benefit ratio at some intermediate size range, as determined by the then current technology, with the benefit/cost ratio then increasing both with semiconductor size increase as well as size decrease.

The prior art has recognized this cost/benefit problem and has provided numerous attempts at minimization thereof. For example, when extremely large power requirements exist, rather than using a single very large semiconductor switch having a poor benefit/cost ratio, several smaller semiconductor switches with improved benefit/cost ratio have been used which collectively have the same or nearly the same current carrying capacity at the required voltage as the large switch, these switches then being connected in parallel to provide the same total current as the larger semiconductor switching device. This alternative operates successfully as long as the switches are essentially identically matched in terms of switching speed and conductivity when turned on. However, if there is mismatch as to only one of the switches, which, for example, will commence conduction prior to the other switches, all of the current will be directed to that one mismatched switch and will lead to burn out of the conducting switch when the ratings of that switch are exceeded. Accordingly, this approach is highly perilous.

A second approach is to use the paralleled switches as discussed above and provide an additional resistance between each switch and the input to the load known as a ballast resistor. This approach can overcome the problem discussed above by placing a resistor in the current path which builds up voltage as the current therethrough increases. However, the addition of resistance in the circuit results in added costs as well as power loss and heating, either or both of the latter of which may be intolerable and both of which are highly undesirable.

Disclosure of Invention

It is therefore apparent that an improved system which provides the ability to use switches providing a maximum benefit/cost ratio,. yet which do not present the deficiencies of the prior art approaches as discussed above is highly desirable.

Briefly, in accordance with the present invention, an approach is provided to accomplish this result in conjunction with an inductive or inductively coupled alternating current circuit. For purposes of illustration, this approach will be discussed with reference to one phase of the stator of a three phase motor. However, it should be understood that this approach can be used in conjunction with any switch controlling an inductive circuit. Also, while inductive coupling between circuits is discussed in the preferred embodiments, it should be understood that such coupling is not a requirement of the invention. Also, while the preferred embodiments specifically reference motor type inductive loads in which gate controlled switching elements couple power from DC circuits to inductive AC circuits, it should be understood that this directionality is not a requirement of the invention, and suitable switching elements can couple power from inductive AC circuits to DC circuits, or bidirectionally.

A plurality of half bridge switches is provided, each half bridge switch being connected to a load in the form of the previously mentioned single phase winding of a three phase motor. The winding formed follows the same circuit as in a conventional three phase winding, however each half bridge switch is connected to an individual insulated winding which follows this circuit. Individual coils may be formed and placed in slots, or several conductors may be would together to form coils which are then placed in slots. Windings are preferably wound together to provide maximum symmetry of load. As in a conventional three phase star connected machine, the windings are coupled to corresponding windings of phases 2 and 3 at a star point; in the case of a delta or mesh connected machine, the windings are joined

appropriately to corresponding windings of phases 2 and 3. In the case of circuits which have a fixed potential point, for example the star connected machine, the fixed potential points of the various independent circuits may be joined together in a common node. The windings are preferably wound together to provide maximum inductive coupling and, in any event, are disposed for maximum inductive coupling. It should be understood that this number of windings, though numbering three, is arbitrary and that the number of windings can be of any number and the number of switches will be equal to the number of windings in the phase 1 coil. The same signal is sent to each of the control electrodes of each of the switches connected to the windings of a single phase circuit, and the identical voltage is provided across each switch. The other phases of the three phase motor are identical to phase 1 except that the synthesized output power is progressively 120 degrees out of phase as is well known. The circuit for the other two phases is identical to the circuit for phase 1 as depicted. The load has been broken up into a plurality of inductively coupled together load elements with a switch placed in series with each load element. Accordingly, the circuitry of the prior art is provided wherein the problem of cost of excessively large switches being ameliorated with the load being altered to provide a plurality of such switches and associated serially connected load elements all connected in parallel between the positive and negative rails and the terminus of the load. While multiple inputs are described, it should be understood that it is merely necessary that there be multiple outputs all acting on windings in parallel. In this way, all problems of prior art attempts to alleviate the benefit/cost ratio are eliminated while the high power required for the load with reduced cost/benefit ration is still obtained.

Brief Description of the Drawings

FIGURE 1 is a circuit diagram of a typical prior art switching circuit for a three phase motor stator;

FIGURE 2 is a circuit diagram of a typical improved prior art switching circuit for a three phase motor stator showing plural switches connected in parallel;

FIGURE 3 is a circuit diagram of a typical further improved prior art switching circuit for a three phase motor stator showing the embodiment of FIGURE 2 with a ballast resistor in series with each switch;

FIGURE 4 is a circuit diagram showing a switching circuit for a dependent three phase star connected motor stator in accordance with the present invention;

FIGURE 5 is a circuit diagram showing a switching circuit for an independent three phase star connected motor stator .in accordance with the present invention;

FIGURE 6 is a circuit diagram similar to that of FIGURE 5 with a delta connected motor stator configuration; and

FIGURE 7 is a circuit diagram showing multiple parallel single phase circuits providing a full bridge transformer utilizing the present invention.

Best Mode for Carrying Out the Invention

Referring first to FIGURE 1, there is shown a typical prior art switching circuit showing for a three phase motor stator connected in a star configuration, which is provided by way of example. This switching circuit is known as a half bridge and runs an inductive load in the preferred embodiment. One of the phases fully depicted includes a positive rail 1 and a negative rail 3 between which are coupled a pair 5 of serially connected transistor switches 7, 9, each switch having a current carrying path and a control terminal 11, 13 respectively. The junction of the switches 7, 9 is coupled to a circuit 15 which is a winding for one phase of the three phase motor in the present example. The circuit 15 is further connected to a star point, which can be but need not be ground potential. The other circuits labeled 5 and the other windings labeled 15 are identical to the similarly referenced structures previously discussed except that the phase of the synthesized alternating current applied to the circuit windings is progressively 120 degrees out of phase with each other as is well known. In this circuit, when both switches 7 and 9 are open, the voltage to the load is floating, whereas, when the switch 9 is open and switch 7 is closed, the voltage at the positive rail 1 is applied to the load 15 and when the switch 7 is open and the switch 9 is closed, the potential of rail 3 is applied to the load 15. Both switches are never on simultaneously since such action would result in a short circuit. Control of each of the switches is by way of the control terminal 11, 13 associated therewith as is well known. In normal operation, in the case of a three phase motor, each of the phases will switch on and off 120 degrees out of phase under control of the control terminals of the respective switches in well known manner. The half bridge circuit 5 includes a pair of catch diodes, diode 17 being biased to conduct in the opposite direction of or antiparallel to the switch 7 and diode 19 being biased to conduct in the opposite direction of the switch 9. The purpose of these diodes is to deal with the inductive current flow from the load 15. When switch 5 turns off, the collapsing magnetic field from the

inductive load maintains the current flow in the circuit with current flowing from the negative rail 3, through the catch diode 19 to the inductive load 15. The transition between the switch 5 being on and off results in a large current spike.

Referring to FIGURE 2, there is shown an improved prior art version of the circuit of FIGURE 1 wherein the single pair 5 of serially connected switches 7, 9 is replaced by a plurality of switches connected in parallel with the control terminals of corresponding switches connected together and the outputs of the switches connected together. Otherwise the circuits of FIGURE 2 is identical to the circuit of FIGURE 1. The purpose of this circuit is to provide the same current carrying capacity to the load 15 except that the current is shown as being split among four sets of switches. While this circuit enhances the cost/benefit ratio as applied to the switches 7, 9, it is essential that the switches 7 and the switches 9 be precisely matched to each other. Otherwise, the first switch to be rendered conductive due to the mismatch will result in essentially all of the current to the load 15 being carried by that first to conduct switch with resultant damage or burnout of that switch when the switch rating is exceeded. Catch diodes (unnumbered) are positioned across each switch as in FIGURE 1 and for the same reason and therefore require no further discussion.

Referring to FIGURE 3, there is shown a further improved prior art version of the circuit of FIGURE 2 wherein each switch 7, 9 is shown without the control terminal and wherein each switch includes a resistor R in series therewith, each resistor generally of the same resistance (though the resistance from switch to switch can also be matched to the associated switch to correct for any offset in the associated switch). The additional resistor in each circuit prevents the mismatched switch from carrying all of the current as discussed in connection with the embodiment of FIGURE 2 since, with increased current through any switch, the voltage across the associated resistor R will increase and retard the increase in current flow therethrough, thereby allowing the other switches to become conductive before the mismatched switch burns out. The obvious shortcoming of this procedure is that the resistors R provide a source of constant power loss and heat when that phase is in operation and the resistors add to the cost of the circuitry. Catch diodes as in FIGURES 1 and 2 are included in FIGURE 3 and have been omitted for clarity to aid in observing the remainder of the circuit.

It is therefore apparent that an improved system which provides the ability to use switches providing a maximum benefit/cost ratio, yet which do not present the deficiencies of the prior art approaches as discussed above is

highly desirable. An approach providing this result for one phase of the stator of a three phase motor is shown in conjunction with FIGURE 4. There are shown a plurality of half bridge switches 21, 23 and 25, each switch being similar to the switch 5 of FIGURE 1 and connected to windings 29, 31, 33 respectively of a phase 1 coil of a three phase motor. It should be understood that the symbol in FIGURE 4 representing the half bridge circuits 5 of FIGURE 1 will be used hereafter to denote such a circuit of similar circuit. The windings 29, 31 and 33 are electrically insulated from each other, but each individually follows the same circuit as a single phase winding of FIGURE 1. The windings 29, 31 and 33 are preferably wound together in the same slots and in the same direction to share the same load, preferably but not necessarily by providing maximum inductive coupling. The windings 29, 31 and 33 are coupled together at node 35. It should be understood that this number of windings, though shown to number three, is arbitrary and that the number of windings can take any number and the number of switches will be equal to the number of windings in the phase 1 coil. The control electrodes of each of the switches 21, 23, 25 are all connected to the identical voltage (though not necessarily the same voltage source) as provided across each switch in FIGURE 1 and denoted as 1 for the positive rail and 3 for the negative rail. The other phases of the three phase motor are identical to phase 1 except that the power synthesized by each phase is progressively 120 degrees out of phase as is well known. The circuit for the other two phases is shown as a box, however, it is identical to the circuit for phase 1 as depicted.

It can be seen that the load has been broken up into a plurality of inductively coupled together load elements with a switch placed in series with each load element. Accordingly, the circuitry of FIGURE 1 is provided wherein the only problem is the cost of excessively large switches with the load being altered to provide a plurality of such switches and associated serially connected load elements all connected in parallel between the positive and negative rails and the terminus of the load.

Referring to FIGURE 5, there is shown a circuit similar to that of FIGURE 4 except that that plural (three in this case) independent three phase star circuits are provided, each circuit with its independent node. The windings associated with each phase will be disposed to provide maximum coupling for each phase as in the embodiment of FIGURE 4.

Referring now to FIGURE 6, there is shown a three phase delta connected motor using the subject invention wherein each phase contains a plurality of winding inductively coupled to each other. It is to be noted that this

circuit does not include a central node. In this circuit, as in the previous circuits, current return is provided by additional half bridges. In the star connected circuits, current flows from DC rail through a half bridge switch, through a phase winding, through the star point, through a second phase winding, through another half bridge switch, and back to the DC rail. In the case of delta connected circuits, current flows from DC rail through a half bridge, through a winding, through a second half bridge and back to the DC rail.

Referring to FIGURE 7, there is shown a multiple parallel single phase full bridge transformer utilizing the concept of the present invention. In this case, by proper control of the switches 5, current can be passed through the primary windings 51, 52 and 53 of the transformer. Full bridge connection is used, similar to the connection of windings in a delta connected motor. The field formed by these windings being cumulative or the sum of the fields developed by each winding. This field is transferred to the secondary winding 54 in standard manner.

Industrial Application

Thus an improved system which provides the ability to use switches providing a maximum benefit/cost ratio, yet which does not present the deficiencies of the prior art approaches is disclosed. The approach is utilised in conjunction with an inductive or inductively coupled alternating current circuit. Though the invention has been described with reference to a specific preferred embodiment thereof, many variations and modifications will immediately become apparent to those skilled in the art. In particular, the current flowing in a single semiconductor switch and thence through an inductive element is limited by placing multiple inductive elements in parallel, with a single series connected switch or half bridge switch pair for each of said multiple inductive elements. In any situation where single inductive circuits are currently used, multiple windings of the present invention may be substituted. It is therefore the intention that the appended claims be interpreted as broadly as possible in view of the prior art to include all such variations and modifications.

Claims

1. A switching circuit for an inductive load which comprises:

   (a) at least one voltage source, each of said at least one voltage source providing essentially the same voltage;

   (b) a plurality of half bridge switching circuits, each said half bridge switching circuit having a pair of serially connected switches, each switch having a current path and a control electrode controlling current flow in its current path, each said half bridge switching circuit coupled across one of said at least one voltage source;

   (c) a node; and

   (d) a plurality of inductive loads, each inductive load coupled between the junction of one of a different said pair of serially connected switches and said node.

2. The switching circuit of claim **1** wherein said plurality of inductive loads are inductively coupled to each other.

3. The switching circuit of claim **2** wherein said plurality of inductive loads is a plurality of coils wound together to form a winding.

4. The circuit of claim **1** wherein each said switch is a transistor having a current path and a control electrode controlling current in said current path.

5. The circuit of claim **2** wherein each said switch is a transistor having a current path and a control electrode controlling current in said current path.

6. The circuit of claim **3** wherein each said switch is a transistor having a current path and a control electrode controlling current in said current path.

7. The circuit of claim 1 further including an antiparallel diode disposed across the current path of each of said switches.

8. The circuit of claim **2** further including an antiparallel diode disposed across the current path of each of said switches.

9. The circuit of claim **3** further including an antiparallel diode disposed across the current path of each of said switches.

10. The circuit of claim **4** further including an antiparallel diode disposed across the current path of each of said switches.

11. The circuit of claim **5** further including an antiparallel diode disposed across the current path of each of said switches.

12. The circuit of claim **6** further including an antiparallel diode disposed across the current path of each of said switches.

13. The circuit of claim **1** wherein said plurality of inductive loads is a coil of a motor.

14. The circuit of claim **2** wherein said plurality of inductive loads is a coil of a motor.

15. The circuit of claim **6** wherein said plurality of inductive loads is a coil of a motor.

16. The circuit of claim **12** wherein said plurality of inductive loads is a coil of a motor.

17. The circuit of claim **13** wherein said motor includes a plurality of phases and a plurality of said coils, one for each phase, each said coil being associated with a different phase of said motor.

18. The circuit of claim **14** wherein said motor includes a plurality of phases and a plurality of said coils, one for each phase, each said coil being associated with a different phase of said motor.

19. The circuit of claim **15** wherein said motor includes a plurality of phases and a plurality of said coils, one for each phase, each said coil being associated with a different phase of said motor.

20. The circuit of claim **16** wherein said motor includes a plurality of phases and a plurality of said coils, one for each phase, each said coil being associated with a different phase of said motor.

21. A switching circuit for an inductive load which comprises:

(a) at least one voltage source having a first rail and a second rail having a voltage different from said first rail, each of said at least one voltage source providing essentially the same voltage;

(b) a first plurality of half bridge switching circuits, each said half bridge switching circuit of said first plurality of half bridge switching circuits having a pair of serially connected switches, each switch having a current path and a control electrode controlling current flow in its current path, the current path of each said half bridge switching circuit coupled to one of said first or second rails of a said at least one voltage source; and

(c) a plurality of inductive loads, each inductive load coupled between the junction of one of a different said pair of serially connected switches of said first plurality of half bridge switching circuits and the other of said first and second rails.

22. The switching circuit of claim **21** wherein said plurality of inductive loads are inductively coupled to each other.

23. The switching circuit of claim **22** wherein said plurality of inductive loads is a plurality of coils wound together to form a winding.

24. The switching circuit of claim **21** further including a second plurality of half bridge switching circuits, each said half bridge switching circuit of said second plurality of half bridge switching circuits having a pair of serially connected switches, each switch having a current path and a control electrode controlling current flow in its current path, each said half bridge switching circuit of said second plurality of half bridge circuits coupled to the other of said first or second rails of a said at least one voltage source; and one of said inductive loads.

25. The switching circuit of claim **22** further including a second plurality of half bridge switching circuits, each said half bridge switching circuit of said second plurality of half bridge switching circuits

having a pair of serially connected switches, each switch having a current path and a control electrode controlling current flow in its current path, each said half bridge switching circuit of said second plurality of half bridge circuits coupled to the other of said first or second rails of a said at least one voltage source; and one of said inductive loads.

26. The switching circuit of claim **23** further including a second plurality of half bridge switching circuits, each said half bridge switching circuit of said second plurality of half bridge switching circuits having a pair of serially connected switches, each switch having a current path and a control electrode controlling current flow in its current path, each said half bridge switching circuit of said second plurality of half bridge circuits coupled to the other of said first or second rails of a said at least one voltage source; and one of said inductive loads.

27. A switching circuit for an inductive load which comprises:

(a) at least one source of DC power, each of said at least one source of DC power providing essentially the same voltage and having a positive and a negative supply;

(b) a plurality of half bridge switching circuits, each said half bridge switching circuit having a pair of serially connected switches, each switch having a current path and a control electrode controlling current flow in its current path, each said half bridge switching circuit coupled across a said positive and a negative supply of one of said at least one source of DC power; and

(c) a plurality of inductive load circuits, each inductive load circuit having two terminations, one of said terminations of each inductive load circuit coupled to an output junction of a different one of said half bridge circuits.

28. The switching circuit of claim **27** wherein said plurality of inductive loads are inductively coupled to each other.

29. The switching circuit of claim **27** wherein said plurality of inductive loads is a plurality of coils wound together to form a winding.

30. A switching circuit connecting inductive alternating circuits and direct current circuits which comprises:

    (a) at least one direct current circuit, each of said at least one direct current circuit operating at essentially the same voltage, each of said at least one direct current circuits having at least one positive and one negative termination;

    (b) a plurality of half bridge switching circuits, each said half bridge switching circuit having a pair of serially connected switches, each switch having a controllable current, each said half bridge switching circuit coupled across said positive termination and said negative termination of one of said at least one direct current circuit, and

    (c) a plurality of alternating current circuits, each of said alternating current circuits having at least two terminations, each of said terminations coupled to each a different output junction of said half bridge switching circuits.

31. The switching circuit of claim **30** wherein said plurality of alternating current circuits is inductively coupled to each other.

32. The switching circuit of claim **30** wherein said plurality of alternating current circuits is a plurality of coils wound together to form a winding.

Figure 1

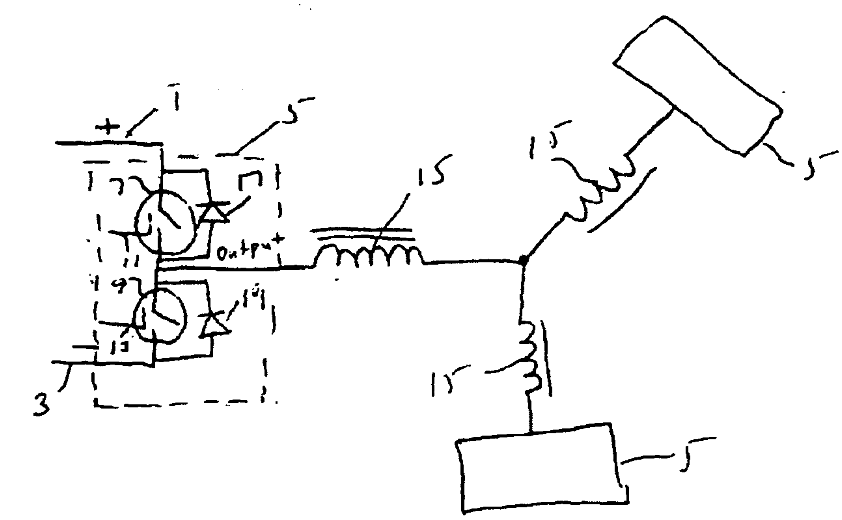


Figure 2

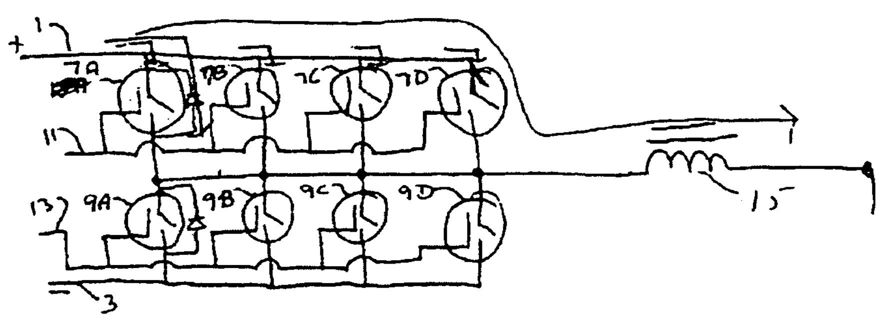


Figure 3

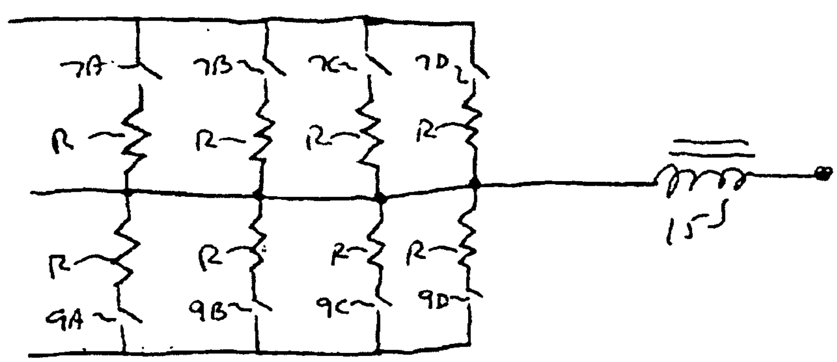


Figure 4

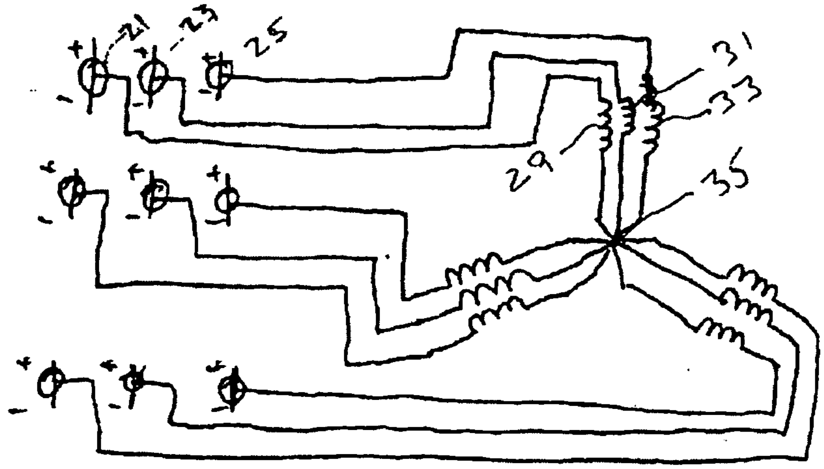


Figure 5

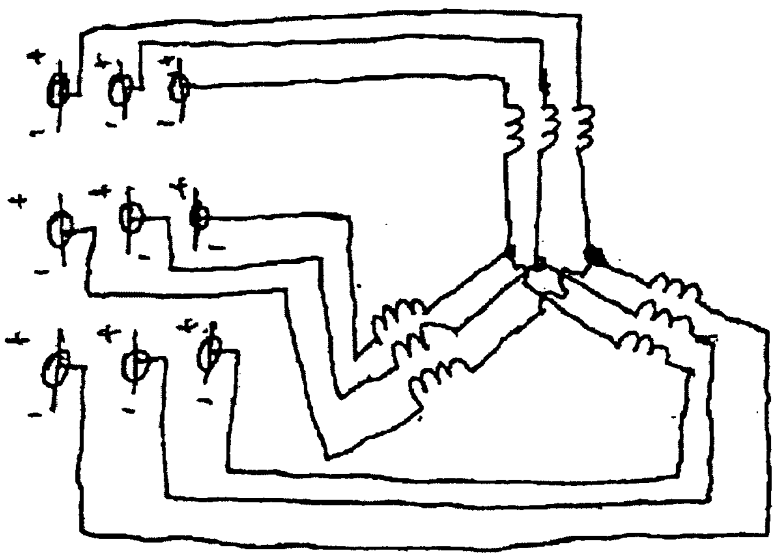


Figure 6

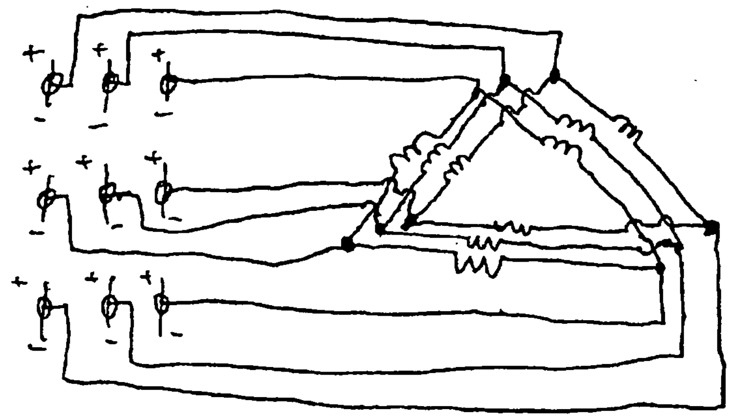
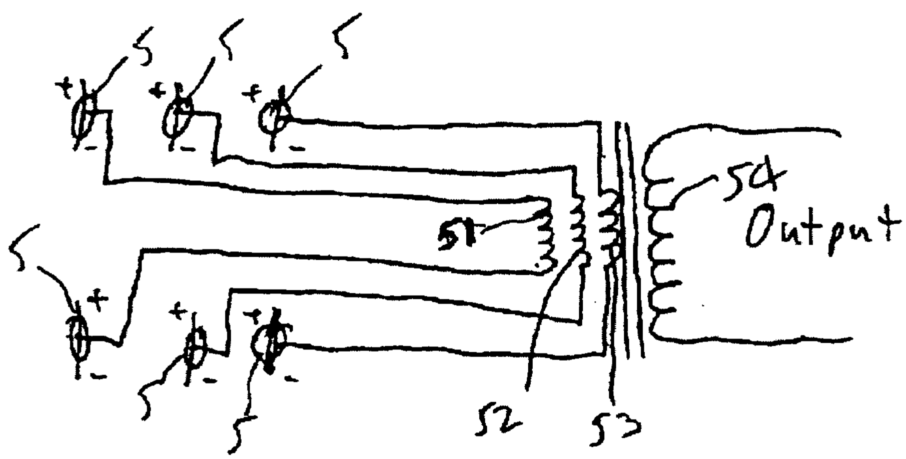


Figure 7



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/18122

A. CLASSIF'CATION OF SUBJECT MATTER

IPC(7) :H02M 7/5387
US CL :307/11, 32; 363/132
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 307/11, 32; 363/132; 318/254

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST
search terms: inductive, parallel , current sharing, half bridge, switch, motor, transformer, coil winding

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,499,186 A (CAROSA) 12 March 1996 (12.03.96), see Figure 2.	1-20,27-32
X	US 5,917,295 A (MONGEAU) 29 June 1999 (29.06.99), see entire document especially column 4, lines 2-50; Figures 1,3.	21-26
A,P	US 6,084,790 A (WONG) 04 July 2000 (04/07/00), see entire document.	1-32
A	US 3,931,553 A (STICH et al) 06 January 1976 (06.01.76), see entire document.	1-32

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
27 SEPTEMBER 2000	17 OCT 2000
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